

Gamma-ray Burst Prompt Emission: Jitter Radiation in Stochastic Magnetic Field Revisited

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ABSTRACT

We revisit the radiation mechanism of relativistic electrons in the stochastic magnetic field and apply it to the high-energy emissions of gamma-ray bursts (GRBs). We confirm that jitter radiation is a possible explanation for GRB prompt emission in the condition of a large electron deflection angle. In the turbulent scenario, the radiative spectral property of GRB prompt emission is decided by the kinetic energy spectrum of turbulence. The intensity of the random and small-scale magnetic field is determined by the viscous scale of the turbulent eddy. The microphysical parameters ϵ_e and ϵ_B can be obtained. The acceleration and cooling timescales are estimated as well. Due to particle acceleration in magnetized filamentary turbulence, the maximum energy released from the relativistic electrons can reach a value of about 10^{14} eV. The GeV GRBs are possible sources of high-energy cosmic-ray.

Subject headings: acceleration of particles — gamma rays: general — radiation mechanisms: non-thermal

1. Introduction

It has been widely discussed that the random and small-scale magnetic field can be generated by Weibel instability (Weibel 1959). The initial magnetic field is formed from the anisotropic distributed plasma disturbed by the certain perturbation. This magnetic field can be amplified by induced currents and finally reach the saturated value. This kind of instability has been considered to occur in the relativistic plasma (Yoon & Davidson 1987; Medvedev & Loeb 1999; Medvedev et al. 2005). The growth and transport of this random and small-scale magnetic field have been confirmed by numerical simulation (Kazimura et al. 1998; Silva et al. 2003; Frederiksen et al. 2004; Hededal & Nishikawa 2005) as well.

Jitter radiation, which is the emission of relativistic electrons in this random and small-scale magnetic field, has been fully investigated in recent years. This radiative mechanism, which is different from the synchrotron process, has been applied successfully to the research of some celestial objects, such as gamma-ray bursts (GRBs; Medvedev 2000; Medvedev 2006a), their afterglows (Medvedev et al. 2007; Workman et al. 2008; Morsony et al. 2009), and jets in the active galaxies (Mao & Wang 2007). Furthermore, Medvedev et al. (2009a) have shown that anisotropy of the jitter radiation pattern and relativistic kinetics can produce the time-resolved spectra of prompt GRB emission. As the magnetic field may play a vital role in the prompt emission of GRB jets (Lyutikov & Blackman 2001; Giannios & Spruit 2005; McKinney & Uzdensky 2010), another theory has also been developed. The general theory of relativistic electron radiation in a sub-Larmor scale magnetic field relevant to the jitter regime includes the anisotropic magnetic field, the effects of trapped electrons, and the case of a large deflection angle of electrons (Medvedev et al. 2010).

The application of the jitter mechanism to GRB prompt emission has been further analyzed. According to a simulation by Sironi & Spitkovsky (2009), jitter radiation can be realized when the strength of electromagnetic fields is reduced so that the wiggler number $K = eBl_{\text{cor}}/m_e c^2$ is smaller than unity, where B is the magnetic field strength and l_{cor} is the length scale of the magnetic field. Kirk & Reville (2010) pointed out that the standard shock scatterings are too weak to provide electrons with the required Lorentz factor.

Considering the aforementioned, it is necessary to revisit the jitter mechanism under the GRB physical conditions. In this paper, we investigate the GRB prompt emission radiated by the relativistic electrons in the stochastic magnetic field. Turbulence, as the dominated physical point, is introduced to the magnetic field generation and the particle acceleration within the framework of the fireball model (Piran 1999). Generally, the GRB prompt spectrum can be fitted by the Band function (Band et al. 1993). As the radiative spectral index below the E_{peak} has been fully discussed by Medvedev et al. (2009a), in this work we do not expect to fit the detailed spectrum for the certain GRB source. Instead, we attempt to

provide the general radiative spectral property above E_{peak} .

The possibility that GRB sources are linked with cosmic rays was proposed by Waxman (1995), Vietri (1995), and Dermer & Atoyan (2004). Dermer & Humi (2001) described the stochastic acceleration of GRB blast waves. The effects of heavy nuclei accelerated by the GRB internal/external shocks have also been taken into account (Murase et al. 2008; Wang et al. 2008). The relativistic electrons radiated in the random magnetic field were considered by some to solve the origin of high-energy cosmic rays (Honda & Honda 2005; Gureev & Troitsky 2008; Honda 2009). However, Medvedev et al. (2009b) concluded that cosmic rays can be linked to the magnetic field generated by Weibel instability as well. These results encouraged us to further investigate the possibilities of cosmic-ray production by jitter radiation under the GRB blast wave framework.

Here, we emphasize the energy of GRB prompt emission released from relativistic electrons in the random magnetic field generated by turbulence. We focus on three questions that are essential to the radiative and turbulent processes: (1) Does the specific simplified jitter radiation that can reproduce the spectral shape and the energy of GRB prompt emission indeed exist; (2) Within the framework of the GRB fireball model, how can the random and small-scale magnetic field be generated by the turbulence, and what is the dominated acceleration process for those relativistic electrons; and (3) In our scenario, can GRBs be linked to high-energy cosmic-ray sources?

In this paper, we extend our turbulent treatment of jitter radiation (Mao & Wang 2007) to the investigation of GRB prompt emission. In Section 2, after reviewing our specific jitter radiation and the stochastic magnetic field, we apply this radiative pattern to GRB prompt emission. We propose that the spectral index of GRB prompt emission is determined by the energy spectrum of turbulence. In Section 3, considering the stochastic magnetic field is decided by the turbulent property, we attempt to obtain the turbulent eddy scale under the GRB physical conditions. To this end, some important parameters, such as ϵ_B , ϵ_e , and electron Lorentz factor, can be obtained. In order to further identify whether jitter radiation is valid, the acceleration timescale, cooling timescale, and wiggler number are estimated. We also speculate, within this specific jitter regime, due to the turbulent effect, that GRBs are possible sources of high-energy. Conclusions are given in Section 4.

2. GRB Prompt Emission

In this section, we propose that the random and small-scale magnetic field is generated by turbulence. The relativistic electron radiation in the random and small-scale magnetic

field is simplified in a one-dimensional case. In this specific jitter regime, the GRB radiative spectral shape is determined by the turbulent energy spectrum.

2.1. Stochastic Magnetic Field

In this work, we simply review the concept of the stochastic magnetic field generated by turbulence (Mao & Wang 2007). The energy spectrum in a general turbulent field can be described as

$$F(q) \propto q^{-\zeta_p}. \quad (1)$$

In the turbulent fluid, through the cascade process, the turbulent energy dissipation field has a hierarchical fluctuation structure. A set of inertial-range scaling laws of fully developed turbulence can be derived. From the research of She & Leveque (1994) and She & Waymire (1995), the energy spectrum index ζ_p of the turbulent field is related to the cascade process number p by the universal relation $\zeta_p = p/9 + 2[1 - (2/3)^{p/3}]$. The Kolmogorov turbulence is presented as $\zeta_p = p/3$. The typical Kolmogorov numbers are $p = 5$ and $\zeta_p = 5/3$.

The stochastic magnetic field $\langle \delta B(q) \rangle$ generated by the turbulent cascade in one-dimension can be given by

$$\langle \delta B^2(q) \rangle \sim K(q) \sim \int_q^\infty F(q') dq', \quad (2)$$

where $q_\nu < q < q_\eta$, q_ν is linked to the viscous dissipation while q_η is related to the magnetic resistive transfer. The Prandtl number $\text{Pr} = 10^{-5} T^4 / n$ constrains the number of q by $q_\eta / q_\nu = \text{Pr}^{1/2}$, where T is the temperature of the plasma and n is the plasma number density (Schekochihin & Cowley 2007).

2.2. Jitter Radiation

The radiation by a single relativistic electron in the small-scale magnetic field was studied by Landau & Lifshitz (1971). The radiation intensity which is the energy per unit frequency per unit time is

$$I_\omega = \frac{e^2 \omega}{2\pi c^3} \int_{\omega/2\gamma_*^2}^\infty \frac{|\mathbf{w}_{\omega'}|^2}{\omega'^2} \left(1 - \frac{\omega}{\omega' \gamma_*^2} + \frac{\omega^2}{2\omega'^2 \gamma_*^4}\right) d\omega', \quad (3)$$

where $\gamma_*^{-2} = (\gamma^{-2} + \omega_{pe}^2 / \omega^2)$, $\omega' = (\omega/2)(\gamma^{-2} + \theta^2 + \omega_{pe}^2 / \omega^2)$ is the frequency in the radiative field, $\omega_{pe} = (4\pi e^2 n / m_e)^{1/2}$ is the background plasma frequency, and γ is the electron Lorentz

factor. This equation presents a general description of diffusive synchrotron radiation. In principle, this radiation is shown in three dimensions.

Following one specific treatment by Mao & Wang (2007), we simplify the above equation in our one-dimensional case as

$$I_\omega = \frac{e^4}{m^2 c^3 \gamma^2} \int_{1/2\gamma_*^2}^{\infty} d\left(\frac{\omega'}{\omega}\right) \left(\frac{\omega}{\omega'}\right)^2 \left(1 - \frac{\omega}{\omega' \gamma_*^2} + \frac{\omega^2}{2\omega'^2 \gamma_*^4}\right) \int dq_0 dq \delta(w' - q_0 + qv) K(q) \delta[q_0 - q_0(q)]. \quad (4)$$

Some interesting cases of the radiative spectrum were fully discussed by GRBs; Medvedev (2000); Medvedev (2006a). In this context, we note that the radiation field is strongly associated with the perturbation field. Thus, the adopted dispersion relation $q_0 = q_0(q)$ is important for the radiative property. In particular, at high frequency, Equation (4) can be simplified by the certain dispersion relation, and the radiative property is determined by the structure of the magnetic field (Mao & Wang 2007).

2.3. Spectrum of GRB Prompt Emission

We first calculate the relativistic electron frequency $\omega_{pe} = (4\pi e^2 n / \Gamma_{sh} m_e)^{1/2} = 9.8 \times 10^9 \Gamma_{sh}^{-1/2} \text{ s}^{-1}$, where Γ_{sh} is the bulk Lorentz factor of the shock. Here, we take the value $n = 3 \times 10^{10} \text{ cm}^{-3}$ as the number density in the relativistic shock; this is consistent with the value used by Medvedev & Loeb (1999). From Equation (4), we see that the radiative frequency is associated with the dispersion relation. Here, we refer to the work of Milosavljević et al. (2006). In their research, the steady state from Weibel instability in the relativistic shock was fully discussed. Having the view angle $\theta \sim \gamma^{-1}$ in the radiative field, we solve that dispersion relation and get

$$\omega = \gamma^2 c q [(1 \pm \sqrt{1 - 4\omega_{pe}^2 / \gamma c^2 q^2}) / 2]^{1/2}. \quad (5)$$

Assuming $\gamma c^2 q^2 \gg 4\omega_{pe}^2$, we obtain $\omega \sim \gamma^2 c q$.

Then, we can integrate Equation (4). At the high-energy band, the radiation frequency $\omega \gg \omega_{pe}$. After inserting the dispersion relation (5) and Equation (2) in Equation (4), we obtain

$$I_\omega \sim \omega^{-(\zeta_p - 1)}. \quad (6)$$

As the single electron spectral index is not affected by the electron Lorentz factor γ , this spectral shape can be viewed as the final result of gross radiative plasma.

However, in our specific case, we further note, as ζ_p is the factor of turbulent scaling law, that the spectral shape of GRB high-energy radiation is determined by the microphysical

turbulent property. Thus, we determine one physical reason to interpret this power-law radiative spectrum shown in Equation (6): The radiative spectral index is fully decided by the cascade process of the turbulent field.

The typical value of ζ_p is the Kolmogorov number $5/3$, given the cascade $p = 5$. However, this number is not universal. As shown in Section 2.1, the different value of ζ_p corresponds to the different cascade number p (She & Leveque 1994; She & Waymire 1995). Therefore, from Equation (6), the radiative spectral index of GRB high-energy emission is allowed a wide range. Moreover, in this paper, we consider the simulation results given by Schekochihin et al. (2004). From their research, the physical processes on the small-scale turbulent dynamo were extensively illustrated. To our interests, in the condition of large Reynolds numbers, the turbulent fluid is viscous dominated and the Prandtl number $\text{Pr} \gg 1$. After the short segment of Kolmogorov scaling index $5/3$, the saturated energy spectrum is deeper and the index turns to the value $7/3$. This simulation result corresponds to the cascade number $p = 7$; thus, we have $\zeta_p = 7/3$ for Kolmogorov form and $\zeta_p = 2.0$ for the calculation from She & Leveque (1994) and She & Waymire (1995).

Finally, we can compare our investigations to the GRB prompt emission data observed by high-energy satellites. From the Burst And Transient Source Experiment observation, above E_{peak} , the flux f_ν has a power-law index of $1.25\text{--}1.4$ (Preece et al. 2000, 2002). From the rough statistics of *Fermi* Gamma-ray Burst Monitor (GBM) data by Guetta & Pian (2009), Ghisellini et al. (2010) and Bissaldi et al. (2011), the spectral index above E_{peak} has a similar value. Thus, the case in which the radiative spectral index $4/3$ is derived from the cascade number $p = 7$ and the turbulent energy spectrum index $\zeta_p = 7/3$ from Kolmogorov form may be one possibility that fits the above observational results. For the following calculations, we take $\zeta_p = 7/3$ as the reference number.

3. Magnetic Field and Particle Acceleration of GRBs

Due to the turbulent effect, the magnetic field can be derived by the scale of the viscous eddy. The electrons can be accelerated to the maximum Lorentz factor about 10^{12} by the scattering in the magnetized filaments. In this scenario, we identify that jitter radiation is valid for the GRB prompt emission and GRBs with maximum energy of about 10^{14} eV might be linked to the possible cosmic-ray sources.

3.1. Magnetic Field

From Equation (2), the magnetic field can be estimated by the following calculation:

$$\langle B \rangle = \left[\int_{q_\nu}^{q_\eta} q^{-\zeta_p} dq \right]^{1/2} = q_\nu^{(1-\zeta_p)/2} / \sqrt{\zeta_p - 1} \quad (7)$$

with the condition $q_\eta \gg q_\nu$. Since q_ν is identified by the viscous property, we take the scale of the viscous eddy to quantify it (Kumar & Narayan 2009; Narayan & Kumar 2009; Lazar et al. 2009). Thus, the number q_ν can be calculated as

$$q_\nu = 2\pi l_{\text{eddy}}^{-1} = 2\pi (R/\Gamma_{\text{sh}}\gamma_t)^{-1} = 6.3 \times 10^{-10} \left(\frac{R}{10^{13} \text{ cm}} \right)^{-1} \left(\frac{\Gamma_{\text{sh}}}{100} \right) \left(\frac{\gamma_t}{10} \right) \text{ cm}^{-1}, \quad (8)$$

where Γ_{sh} and γ_t are the Lorentz factor of shock and the turbulent eddy, respectively. At the fireball radius 10^{13} cm, taking the turbulent spectrum $\zeta_p = 7/3$, we have a magnetic field of about 1.2×10^6 G. This result is fully consistent with the estimation from the fireball internal shock model (Piran 2005). As presented in Section 2.1, the value q_η can be obtained by $q_\eta = Pr^{1/2}q_\nu$. We can obtain the plasma temperature by the form $T = m_e c^2/k$; k is the Boltzmann constant. Finally, we have magnetic resistive scale q_η as

$$q_\eta = 3.9 \times 10^2 \left(\frac{n}{3 \times 10^{10} \text{ cm}^{-3}} \right)^{-1/2} \left(\frac{T}{5.6 \times 10^9 \text{ K}} \right)^2 \text{ cm}^{-1}. \quad (9)$$

Moreover, the micro-parameter ϵ_B can be achieved as

$$\epsilon_B = 5.2 \times 10^{-2} \left(\frac{B}{1.2 \times 10^6 \text{ G}} \right)^2 \left(\frac{\Gamma}{100} \right)^3 \left(\frac{\delta t}{1 \text{ s}} \right)^3 \left(\frac{E_k}{10^{51} \text{ erg}} \right)^{-1}, \quad (10)$$

where δt is the time variability of the radiative pulse and E_k is the kinetic energy of the relativistic shell. Following the estimation from Medvedev (2006b) we can obtain $\epsilon_e = \sqrt{\epsilon_B} = 0.23$ through the typical value $\epsilon_B = 0.052$.

3.2. Acceleration and Timescales

Particle acceleration is strongly involved in the physical processes described in Section 3.1. Hededal et al. (2004) found that the relativistic electrons have a power-law distribution, but the acceleration is local. Nishikawa et al. (2006) confirmed that the electrons are not *Fermi*-accelerated and the processes in the relativistic collisionless shock are dominated by Weibel instability. The three-dimensional simulation presented in detail that the Weibel instability excited in collisionless shocks is responsible for electron acceleration

(Nishikawa et al. 2009). In this paper, we demonstrate that, under our scenario, electron acceleration in the magnetized current filaments is vital for the jitter radiation.

Electron energy distribution is not a power law under a turbulent process. Schlickeiser (1984, 1985) already found an ultra-relativistic Maxwellian energy distribution. Stawarz & Petrosian (2008) used this Maxwellian energy distribution to produce the synchrotron and inverse Compton spectra. Recently, the Maxwellian electron component has been found through simulation (Spitkovsky 2008) and has been applied to GRB research (Giannios & Spitkovsky 2009). In this context, we estimate the average Lorentz factor of relativistic electrons given by Giannios & Spitkovsky (2009): $\langle \gamma \rangle = \epsilon_e \Gamma m_p / m_e$. Using the number $\epsilon_e = 0.23$, which we have derived, and $\Gamma = 100$, we obtain $\langle \gamma \rangle = 3.6 \times 10^4$.

In general, stochastic acceleration has been fully discussed by Schlickeiser (1989a,b), Dermer et al. (1996), and Stawarz & Petrosian (2008). The acceleration timescale was calculated by Schlickeiser (1989a,b) and Petrosian & Liu (2004). From their studies, the particles are buried in a regular and external magnetic field. The magnetic field is generated by macroscopic turbulence (Sironi & Goodman 2007). However, this is not our physical situation. Alternatively, Honda & Honda (2005) and Honda (2009) mentioned the acceleration process in the random magnetic field. The electrons can be effectively accelerated in the magnetized current filaments. This acceleration process is consistent with the physics of Weibel instability and our magnetic field generation. Here, we apply this kind of process. The acceleration timescale can be calculated as

$$t_{\text{acc}} = \left(\frac{6^{1/2}\pi}{8}\right) \left(\frac{c}{L}\right) \left(\frac{E}{eBU}\right)^2 = 1.4 \times 10^{-12} \left(\frac{E}{\text{MeV}}\right)^2 \left(\frac{B}{1.2 \times 10^6 \text{ G}}\right)^{-2} \left(\frac{L}{1.0 \times 10^{10} \text{ cm}}\right)^{-1} \left(\frac{U}{0.1c}\right)^{-2} \text{ s}, \quad (11)$$

where we take the upstream speed $U \sim 0.1c$. The turbulent length scale L should be given by $q_\eta < L^{-1} < q_\nu$. In the equation above, we use $L \sim 10^{10} \text{ cm}$ as a reference number. The cooling timescale can be estimated as

$$t_{\text{cool}} = \frac{6\pi m_e c}{\sigma_T \gamma B^2} = 1.5 \times 10^{-8} \left(\frac{\gamma}{3.6 \times 10^4}\right)^{-1} \left(\frac{B}{1.2 \times 10^6 \text{ G}}\right)^{-2} \text{ s}. \quad (12)$$

From the calculations above, at the region 10^{13} cm from the burst center, for a single electron with the average Lorentz factor $\gamma \sim 10^4$, at the MeV band, we have $t_{\text{acc}} < t_{\text{cool}}$, meaning that the particle acceleration is effective for jitter radiation.

Recently, Medvedev et al. (2009c) investigated the cooling timescale in detail. The relativistic plasma frequency of the protons is given by $\omega_{pp} = 3.8 \times 10^8 (n/3 \times 10^{10} \text{ cm}^{-3})^{1/2} \text{ s}^{-1}$; we can obtain the parameter $T_{\text{cool}} = t_{\text{cool}} \omega_{pp} < (10 - 50)$. Following their analysis, this means that cooling is very fast with strong radiative loss; thus, *Fermi* acceleration is impossible.

In our scenario, the electron scattering in the magnetized filaments can be a self-consistent way for the particle acceleration.

In order to further illustrate the validation of jitter radiation, first, we note that the characteristic correlation scale of the magnetic field l_{cor} should be less than the typical Larmor radius r_L of a relativistic electron. The correlation scale $l_{\text{cor}} \sim (0.1 - 1)l_{\text{sk}}$, $l_{\text{sk}} = c/\omega_{pe}$ is the skin depth. For a relativistic electron the Larmor radius is $r_L \sim \gamma m_e c^2 / eB$. If $l_{\text{cor}} < r_L$, we obtain $\gamma > 2.2 \times 10^4$ for a magnetic field $B \sim 1.2 \times 10^6$ G and $l_{\text{cor}} \sim l_{\text{sk}}$. Then, we calculate the wiggler parameter (Sironi & Spitkovsky 2009; Medvedev et al. 2010) as

$$K = \frac{eBl_{\text{cor}}}{m_e c^2} = 2.2 \times 10^4 \left(\frac{B}{1.2 \times 10^6 \text{ G}} \right) \left(\frac{\Gamma_{\text{sh}}}{100} \right)^{1/2} \left(\frac{n}{3 \times 10^{10} \text{ cm}^{-3}} \right)^{-1/2}. \quad (13)$$

Thus, we obtain $1 < K < \gamma$. Following the analysis by Medvedev et al. (2010), the jitter regime can be satisfied in the condition of a large electron deflection angle. We further calculate the deflection angle $\theta = eBl_{\text{cor}}/\gamma m_e c^2$. using numbers $B \sim 1.2 \times 10^6$ G and $\Gamma_{\text{sh}} \sim 100$, we obtain $\theta < 1$.

3.3. GeV GRBs and Possible Cosmic-ray Origin

We further obtain some interesting results of high-energy emission associated with the turbulence. As mentioned by Honda & Honda (2005), the particles can be accelerated by interaction with the local magnetic filaments. Virtanen & Vainio (2005) studied the electron energy gained by turbulent scattering. Since we have obtained the magnetic field by the turbulent viscous eddy, we can calculate the maximum Lorentz factor of electrons as

$$\gamma_{e,\text{max}} = eB/q_\nu m_e c^2 = 1.1 \times 10^{12} \quad (14)$$

with $B = 1.2 \times 10^6$ G. Thus, at distance $R \sim 10^{13}$ cm from the GRB explosion center, due to relativistic turbulence, the acceleration process can produce electrons with extremely high Lorentz factor values up to 10^{12} . This value is much larger than the estimation number of Kirk & Reville (2010). The lower Lorentz factor of electrons given by Kirk & Reville (2010) comes from *Fermi* acceleration (Achterberg et al. 2001).

As the turbulent region is 10^{13} – 10^{16} cm from the burst center, where $R \sim 10^{13}$ cm is the optical-thin radius and $R \sim 10^{16}$ cm is the deceleration radius of the fireball, we obtain the maximum frequency of the jitter radiation $\omega_{\text{max}} \sim 10^{11} - 10^{18}$ eV. The maximum value is strongly dependent on the emission region related to the fireball radius. In order to further constrain the released energy in the jitter regime, we have the constraint that comes from the results of Medvedev et al. (2010). In the jitter radiation with the condition

of a large electron deflection angle, the break radiative frequency has been derived as $\omega_b \sim (c/l_{\text{cor}})^3 (eB/\gamma m_e c)^{-2}$. Our calculations in this paper are valid if we have the radiation frequency below this break. As this break frequency dependent on γ , we obtain the maximum value of the break $\omega_{b,\text{max}} \sim 10^{11}$ eV if $B \sim 1.2 \times 10^6$ G and $\Gamma_{\text{sh}} \sim 100$. Finally, we use $t_{\text{acc}} = t_{\text{cool}}$ and obtain the maximum possible energy of electrons

$$E = 2.5 \times 10^{14} \left(\frac{U}{0.1c} \right) \left(\frac{L}{1.0 \times 10^{10} \text{ cm}} \right)^{1/2} \left(\frac{\gamma}{3.6 \times 10^4} \right)^{-1/2} \text{ eV}. \quad (15)$$

This maximum energy is dependent on the Lorentz factor γ of electrons and the turbulent length scale L .

Although some other mechanisms, such as thermal emission, synchrotron self-Compton, and Comptonization, are proposed to modify the spectrum shape (Toma et al. 2010; Pe’er et al. 2010), we see that the MeV–GeV GRB emissions might be reproduced by jitter radiation in our specific case. Some GRBs detected by *Fermi* satellite may support our speculation. GRB 080916C (Abdo et al. 2009) and GRB 090217A (Ackermann et al. 2010) are the typical examples. In their spectra, we cannot find any cutoff evidence toward the high-energy frequency. With the same spectral index, the spectra might be extrapolated to the higher energy band, which is out of the energy threshold of *Fermi* observation. Thus, in our specific case, the GRB jitter regime naturally provides the link to the high-energy cosmic rays. These GRBs are the possible sources of cosmic-ray.

The estimated electron maximum energy is roughly consistent with the first knee at about 10^{15} eV seen in the cosmic-ray spectrum (e.g., Antoni et al. 2005). Within the framework of our simple treatment, this maximum energy is still below the Greisen–Zatsepin–Kuzmin limit. We propose that the first knee at about 10^{15} eV in the cosmic-ray spectrum might be due to variations in electron Lorentz factor and related timescales in our calculations. The energy observed above 10^{18} eV could be explained by some other mechanisms in which the heavy nuclei are involved (Honda 2009).

Although our estimated maximum energy can reach the GeV band, in general, above 100 MeV, with the average number $\gamma \sim 10^4$, the acceleration timescale is larger than the cooling timescale, and the jitter radiation does not work. Thus, in our scenario we do not expect many more GeV GRBs.¹

The high-energy spectral properties are more complicated. With the collection data from Ghisellini et al. (2010), about 11 GRBs observed by *Fermi* Large Area Telescope (LAT), and the constraints by Guetta et al. (2010), we find that some GRB GeV emissions detected by

¹See Fan (2009) for the "traditional" interpretations about non-detection GeV emissions.

LAT can not be explained by our simple treatment. Recently, Kumar & Barniol Duran (2009) and Kumar & Barniol Duran (2010) proposed that GeV emission detected by *Fermi* originates from the afterglow and is produced by the external shock. This is questioned by Piran & Nakar (2010). From the calculation in the external shock model (Barniol Duran & Kumar 2010), the magnetic field is about $10 \mu\text{G}$, which is a very low number compared with our estimation. Thus, our treatment cannot apply to the afterglow/external shock scenario. Of course, other explanations for the GRB MeV-GeV emissions cannot be ruled out (Zhang & Pe’er 2009; Gao et al. 2009; Wang et al. 2009; Li 2010).

4. Conclusion

Although jitter radiation as an explanation of GRB prompt emission has recently been challenged by Sironi & Spitkovsky (2009) and Kirk & Reville (2010), by applying the specific case of relativistic electron radiation in the random and small-scale magnetic field, we have successfully reproduced the radiative spectral index above energy E_{peak} . The spectral variability of GRB emission below E_{peak} has been determined by Medvedev et al. (2009a), so the problem of the “synchrotron line of the death” (Preece et al. 1998; Savchenko & Neronov 2009) might be solved as well.

In our scenario, the random and small-scale magnetic field is generated by turbulence. The GRB radiative property in the jitter regime is determined by the turbulent structure. We also declare that particle acceleration under Weibel instability in the relativistic shock may differ from *Fermi* acceleration. As *Fermi* acceleration is inefficient for jitter radiation, in our work, the acceleration process in the magnetized filamentary turbulence plays a key role in explaining the GRB prompt emissions.

We have shown that jitter radiation can produce GRB high-energy photons at the MeV-GeV band. We further suggest that our specific jitter regime of GRBs could be one of the explanations for high-energy cosmic-ray origin. In contrast, Zou et al. (2009) have discussed many kinds of inverse Compton processes for GRB high-energy emission. As pointed out by Kirk & Reville (2010), the Compton mechanism, which produces photons from jitter radiation scattered by the thermal/nonthermal electrons, may modify the original spectral property. We will investigate this more complicated process in future work.

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